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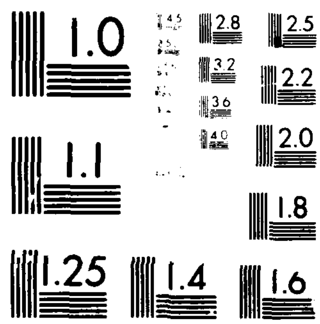

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ISSUES AND POTENTIAL PROGRAM ON DENATURED FUEL UTILIZATION

Prepared For

Prepared By

Southern Science Applications, ~~Inc.~~ New
~~Division of Black & Veatch~~
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This study was performed to review the issues involved in implementing an alternative fuel cycle that may contribute to reducing the risk of nuclear weapons proliferation. The objectives of this report are to discuss the political, technical, and economic issues that will affect the acceptance and use of the denatured fuel cycle and to identify a possible program plan typical of that which would be required to foster acceptance by U.S. utilities.

One of the more promising methods involves the use of a mixture of uranium and thorium oxides as reactor fuel (denatured fuel cycle). By reducing U-238 content, the amount of plutonium produced can be correspondingly reduced. However, thorium in the fuel results in the production of U-233. For current LWRs, a reasonable compromise would reduce plutonium production by a factor of 4 or more, while avoiding the existence of uranium enriched to more than 12% U-233 or 20% U-235. Further reduction in plutonium production could be accomplished, but only by using fuel more highly enriched in U-233 or U-235. To avoid unwarranted impact on U_3O_8 resource requirements, reprocessing and recycle of the U-233 produced will be necessary.

Factors that would affect the acceptance and use of denatured fuel by the nuclear power industry are considered.

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December 1978

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U.S. ARMS CONTROL AND DISARMAMENT AGENCY

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I. INTRODUCTION AND SUMMARY

This study was performed for the U.S. Arms Control and Disarmament Agency, under Contract No. AC8NC109 (Task I), to review issues involved in implementing an alternative fuel cycle that may contribute to reducing the risk of nuclear weapons proliferation. The objectives of this report are to discuss the political, technical, and economic issues that will affect the acceptance and use of the denatured fuel cycle and to identify a possible program plan typical of that which would be required to foster acceptance by U.S. utilities.

The President has proposed an International Fuel Cycle Evaluation Program in an effort to reduce the risk of worldwide nuclear weapons proliferation. In response to the President's proposal, the U.S. Arms Control and Disarmament Agency initiated studies that seek means to alleviate the potential proliferation problem as future energy requirements increase the need for nuclear power plants throughout the world.

One of the more promising methods involves the use of a mixture of uranium and thorium oxides as reactor fuel (denatured fuel cycle). By reducing U-238 content, the amount of plutonium produced can be correspondingly reduced. However, thorium in the fuel results in the production of U-233, a fissile material nearly as good as plutonium for weapons use. Consequently, it is necessary to have some U-238 in the fuel to dilute the U-233 produced, thereby precluding its use as weapons material (at least without isotope separation, a difficult and expensive process). Thus, a compromise is necessary between the reduction in quantity of plutonium produced and the percent U-233 in the uranium of the discharged fuel. For current LWRs, a reasonable compromise would reduce plutonium production by a factor of 4 or more, while avoiding the existence of uranium enriched to more than 12% U-233 or 20% U-235. Further reduction in plutonium production could be accomplished, but only by using fuel more highly enriched in U-233 or U-235. To avoid unwarranted impact on U_3O_8 resource requirements, reprocessing and recycle of the U-233 produced will be necessary.

Recognizing the potentially good proliferation-resistance of the denatured fuel cycle, it is necessary to consider the factors that would affect its acceptance and use by the nuclear power industry. These considerations involve technical and economic issues, as well as possible incentives that may be necessary for adoption of the denatured cycle. Although the industry realizes that an unsuitable fuel cycle can lead to proliferation problems, the experience accumulated with the present uranium cycle is frequently interpreted to indicate reasonable proliferation resistance. Furthermore, since it is probably impossible to develop a reactor system and fuel cycle that are proliferation-proof, the basic industry concept of the problem is a matter of degree. Therefore, the basic subjective/ political issue affecting utilization of a denatured U-Th fuel cycle is whether the industry, including the consumer, believes that the use of this cycle would have a measurable effect on an international political issue and that the advantages justify any additional cost.

In this report, a number of issues are presented together with a survey of pertinent information from other studies relating to some of the principal issues. Finally, a preliminary program for the demonstration of the denatured fuel cycle is presented. This program identifies the major projects that would be required and projects that commercial utilization could begin around 1990, with complete recycle of U-233 by about 1995.

II. DENATURED FUEL UTILIZATION ISSUES

A. Safety and Licensing

Introduction of an alternate fuel cycle concept (or even the introduction of a new fuel design within an existing concept) requires that the safety of the new cycle be demonstrated both analytically and in a practical demonstration and prototype test program. Generally, the denatured fuel cycle is not expected to require plant modification: the safety/licensing issues revolve about the performance characteristics of the U-Th oxide fuel. Next to economics, the licensing issue will likely be the principal underlying reason for industry opposition to the denatured fuel cycle. Much of the anticipated industry resistance to a new fuel cycle would derive from a reluctance to become entangled in a licensing process that could involve considerable uncertainties, long time delays, and unpredictable expenses.

The Electric Power Research Institute (EPRI) funded a Combustion Engineering (CE) study[1] that explored many aspects of thorium fuel cycles in PWRs, including the safety and licensing considerations. The CE study was performed for fully-enriched U-235/ThO_2 fuel as the startup core and for recycle cores that have approximately 51% fissile uranium inventory. Table 1 compares the physics parameters important to safety for the startup (or non-recycle) cores on both the thorium fuel cycle and the reference LWR UO_2 (U-235) cycle. Table 2 is a comparison of these same parameters for a ThO_2-based core at near recycle equilibrium to those of a UO_2 equilibrium core operating on a self-generated plutonium recycle basis. The only parameter which invokes some concern is the moderator temperature coefficient for a beginning-of-cycle thorium recycle core. Although a small positive value is shown in Table 2, the text discusses the analysis and concludes that more accurate analysis would probably yield a negative value.

Using the physics parameters in Tables 1 and 2, the CE study evaluated safety consequences of the events shown in Table 3. None of these events is predicted to result in consequences appreciably more severe than the reference core. In some cases the behavior of the thorium core is more benign. These results are for thorium cores containing higher enrichments than those characteristic of the denatured fuel cycle. Therefore, the physics parameters for the denatured fuel cycle can be expected to more closely resemble the reference LWR fuel cycle with Pu recycle.

Table 1 COMPARISON OF CORE CHARACTERISTICS FOR NON-RECYCLE CORES

(Reproduced from EPRI NP-359, Ref. 1)

	UO_2(U-235) CORE EQUILIBRIUM CYCLE	ThO_2(U-235) CORE
Effective Delayed Neutron Fraction		
BOC	.00625	.00620
EOC	.00543	.00551
Prompt Neutron Lifetime ($\times 10^{-6}$ sec)		
BOC	23.1	21.3
EOC	25.9	26.2
Inverse Soluble Boron Worth (ppm/%$\Delta\rho$)		
BOC	106	114
EOC	101	95
Fuel Temperature Coefficient ($\times 10^{-5}\Delta\rho/°F$)		
BOC	-1.20	-1.37
EOC	-1.29	-1.33
Moderator Temperature Coefficients[(1)] ($\times 10^{-4}\Delta\rho/°F$)		
BOC	-0.07	+0.26
EOC	-2.41	-1.39
Control Rod Worth (% of Equilibrium Cycle UO_2 Case)[(2)]		
BOL	Reference	90
EOL	Case	101

[(1)] Does not include potentially important core spatial effects which would make this coefficient more negative.

[(2)] For indicated fuel type not core average.

Table 2 COMPARISON OF CORE CHARACTERISTICS FOR RECYCLE CORES

(Reproduced from EPRI NP-359, Ref. 1)

	UO_2-BASED CORE EQUILIBRIUM CYCLE SGR Pu RECYCLE[(1)]	ThO_2-BASED CORE NEAR-EQUILIBRIUM CYCLE
Effective Delayed Neutron Fraction		
BOC	0.00567	0.00512
EOC	0.00518	0.00481
Prompt Neutron Lifetime ($x10^{-6}$ sec)		
BOC	17.0	20.5
EOC	19.5	25.7
Inverse Soluble Boron Worth (ppm/%$\Delta\rho$)		
BOC	149	118
EOC	130	95
Fuel Temperature Coefficient ($x10^{-5}\Delta\rho/°F$)		
BOC	-1.08	-1.34
EOC	-1.17	-1.32
Moderator Temperature Coefficients[(2)] ($x10^{-4}\Delta\rho/°F$)		
BOC	-0.95	+0.56
EOC	-3.73	-1.18
Control Rod Worth (% of Equilibrium Cycle UO_2 Case)[(3)]		
BOL	76	94
EOL	81	101

(1) Taken from Reference 12, SGR-self generated recycle.

(2) Spatial effects included in SGR Pu recycle core values.

(3) For indicated fuel type not core average.

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Table 3 EVENTS ANALYZED FOR PWRs
(Reproduced from EPRI NP-359, Ref. 1)

CONDITION II OCCURRENCES

1. CEA Withdrawal
2. CEA Misoperation
3. Uncontrolled Boron Dilution
4. Loss of Coolant Flow
5. Idle Loop Startup
6. Loss of Load or Turbine Trip
7. Loss of Normal Feedwater
8. Loss of AC Power
9. Excess Load

CONDITION III OCCURRENCES

1. Small LOCA
2. Minor Steam-Line Break
3. Inadvertent Loading of a Fuel Assembly in an Improper Position

CONDITION IV OCCURRENCES

1. Large LOCA
2. Steam Generator Tube Rupture
3. Major Steam-Line Break
4. CEA Ejection
5. Fuel Handling Accident

Analysis performed at the Massachusetts Institute of Technology (MIT) indicates[2] that an LWR operating on a thorium cycle should have a drier lattice (increased fuel-to-coolant volume ratio) than the present UO_2 fuel cycle in order to achieve optimum performance. The safety implications of the drier-lattice fuel design have not been assessed thoroughly, although some work on the thermal-hydraulic limitations of this fuel modification is being carried out at MIT.

Oak Ridge National Laboratory (ORNL) sponsored a General Electric (GE) study[3] to investigate the utilization of thorium in BWRs. A summary of the operation and safety findings is quoted below:

> From consideration of BWR operations and safety, the thorium fuel designs appear to offer some advantageous trends over the typical UO_2 fuel designs. The less negative dynamic void reactivity coefficients tend to reduce the severity of reactor overpressurization-type accidents, improve reactor stability, and enhance the BWR's automatic load following (ALF) capabilities. The effects of thorium on the LOCA would probably be small, with the shorter ℓ^* and smaller β of some designs tending to reduce residual fission power.
>
> The smaller void reactivity coefficients of thorium fuels will result in flatter axial power shapes and improved cold shutdown margin. The flatter burnup slopes will reduce power mismatch between channels and improve departure from nucleate boiling (MCPR) margins. Fuel reliability (MLHGR) and LOCA (MAPLHGR) margins will be improved.
>
> The U-233 enriched ThO_2 fuels exhibit positive steam void reactivity coefficients. This can be controlled by addition of U-238 to the fuel. The optimum U-238 addition to U-233/Th-232 fuels is less than that required to "denature" the fuel (less than the amount of U-238 required to reduce the U-233 enrichment below 12%). In realistic situations pure U-233 will not be available, and the presence of other nuclides such as U-234 and U-236 has a negative effect on reactivity coefficients (the opposite effect of U-233).

B. Operation and Fuel Performance

Operation/performance characteristics of the U-Th oxide fuel that must be evaluated in assessing the acceptability of the denatured fuel cycle include, in addition to in-reactor performance during the power-production period, all factors related to the nuclear fuel cycle. These factors include the following:

- uranium and thorium ore availability;
- conversion to oxide form and suitable blending operations;
- fuel fabrication;
- reactor operation;
- spent fuel storage;
- reprocessing; and
- recycle and waste management.

Within the reactor core, operation with the denatured fuel is not expected to differ greatly from corresponding operation with conventional uranium oxide fuel, except to the extent operations may be affected by the physical properties of the mixed oxide fuel, as discussed previously. Presumably, plentiful supplies of thorium ore are available. However, there is some concern about appropriate methods of mixing the uranium and thorium oxides—i.e., blending or co-precipitation—to assure a uniform mixture that will not segregate or result in unacceptable hot-spots during reactor operation. Fuel fabrication techniques must also assure acceptable performance characteristics of pressed-and-sintered pellets (or vibratory-compacted fuel elements).

Storage of spent denatured fuel will not likely differ significantly from storage of conventional uranium fuel. However, in chemical reprocessing, it is known that thorium oxide is more difficult to dissolve than uranium oxide, so a different head-end process (modified Thorex process) than that used for the uranium fuel cycle will likely be required. In addition to recovery of the thorium and uranium, some plutonium will be recovered. Disposition of the plutonium (and fission-product wastes if different) must also be considered.

In addition, recycle of the uranium (then containing U-233) would impose additional requirements, such as remote fuel fabrication facilities as a result of U-232 in the fuel, blending with highly-enriched uranium to restore initial reactivity, and the accommodation of increasing parasitic absorption due to U-234 and U-236 accumulation.

As described in the preceding safety discussion, the use of denatured thorium fuel in BWRs can possibly improve operating performance. The operating characteristics of PWRs on the denatured thorium fuel cycle are judged to be comparable to the UO_2 fuel cycle. Since the recycled thorium fuel will be radioactive, the procedures for handling fresh fuel will have to be revised. This may require modifications in the fuel handling areas of nuclear power plants.

The principal area needing additional study and irradiation experience is the fuel performance of the denatured thorium fuel cycle. Both the fuel for the original core loading and the equilibrium recycled fuel should receive sufficient irradiation R&D to permit statistically significant fuel performance parameters to be measured and characterized in revisions to current UO_2 fuel performance codes. The parameters of interest include the following:

- fuel densification;
- pellet-clad interaction (ratcheting);
- fuel swelling; and
- fission gas pressure.

Prior irradiation experience has been on the fully enriched thorium fuel cycle. Reference 4 summarizes the principal irradiation experience (taken from References 5 and 6) as reproduced below:

Thorium and Thorium-Uranium Oxides (ThO_2 and $(U,Th)O_2$)

Thorium oxide has been studied more extensively than any other thorium compound. A number of irradiation experiments involving ThO_2 are reported in Reference 10, including:

1. dense pellets with 6.36 w% UO_2 in the Borax IV BWR blanket;

2. the first cores of the Indian Point PWR and Elk River BWR, which also used pressed and sintered pellets of ThO_2-UO_2;

3. PyC coated ThO_2 microspheres have been extensively tested with the support of the HTGR fuel development program;

4. coated particles of $(U,Th)O_2$ have been extensively tested as potential HTGR fuels.

A detailed summary of the irradiation behavior of ThO_2 and $(Th,U)O_2$ has been published by Olsen.[6] In this work, the irradiation behavior of ThO_2 and $(Th,U)O_2$ in three different forms were compared. The forms were (1) vibratory compacted sol-gel powder, (2) arc-fused $(Th,U)O_2$ rods, and (3) rods containing pressed and sintered pellets.

The conclusion reached by Olsen et al.[6] is that all three forms of thoria/urania fuel performed well at burnups up to 80 MWd/kg HM. There was no evidence of breakaway swelling or sudden increases in fission gas release. The average linear heat rates for these fuel rods were between 300 and 350 w/cm (9.8 to 11.5 kw/ft).

Thoria-Plutonia Fuels $(Th,Pu)O_2$

Very little work has been done with this fuel. One $(Th,Pu)O_2$ fuel rod was included in the work described by Olsen et al.[6] but examination of this rod was incomplete at the time reference 6 was written. Preliminary examination of this fuel, which had been irradiated to a burnup of 29 MWd/kg HM at an average linear heat rate of 245 w/cm (8 kw/ft), showed a microstructure similar to $(Th,U)O_2$ irradiated under the same conditions. Clearly, the deficiency of information about the performance of thoria-plutonia fuels must be addressed if large scale use of the thorium fuel cycle in LWRs and CANDUs is to be seriously considered.

Because of the anticipated better behavior of thorium metal, metallic fuel could perhaps be an alternative in the denatured fuel cycles.

C. Reprocessing and Remote Fabrication

Numerous studies have confirmed that the realization of U_3O_8 resource savings in the denatured fuel cycle is dependent upon recycle, at least of the U-233 produced. Therefore, introduction of the denatured thorium fuel cycle will require a demonstration of reprocessing and fabrication capability and costs. The estimates regarding extent of R&D and recycled fuel costs associated with the required pilot scale plants vary considerably in the literature.

A good overview of reprocessing options is contained in Reference 7. Table 4 shows the applicability of 14 processes to 7 different fuel types. Since the Thorex process was developed for metallic thorium it is not shown as being applicable to ThO_2. However, a modified Thorex process could dissolve thoria although the dissolution rate is significantly slower than that for urania. Table 5, also taken from Reference 7, indicates the results of a value engineering assessment of the different processes. Each process is rated on a scale of 1 to 10 for the given descriptor and each descriptor has a weighting factor given under the column heading "rank." Based on these ratings the Halide process is shown to be slightly superior to the Thorex process. However, these ratings were not performed for the specific task of assessing the preferred reprocessing scheme for the mixed oxide U-Th-PuO_2 fuel that will be produced by the denatured fuel cycle. Table 6 (from Reference 7) gives a summary of cost estimates for the 14 processes. Again Halide volatility is shown to be cheaper than the Thorex process. Note that both of these processes are cheaper than Purex. The costs are estimates of processing 1 kilogram of fuel per day based on flowsheets showing blocks of equipment. The costs do not include such further costs as head-end treatment, fuel transportation, inventory, safeguards requirements, safety requirements, and R&D.

An evaluation of the reprocessing technology required for fuel elements containing fuel pins of Pu-U-ThO_2 and pins of enriched UO_2 has been developed in Reference 8. The pins would be physically sorted and the former pins would follow the type of process which is required to process the denatured thorium fuel. Figure 1 gives the flowsheet and Table 7 indicates the recovery flow rates. Table 8 details the additional steps in the thoria process flowsheet beyond that required for the reference LWR Purex process. The costs of this process compared to the Purex cost was estimated to be from 1.25 to 2.0

greater. The actual cost in 1975 dollars is estimated at \$200 to \$320/kg which does not include any shipping costs.

A more recent estimate[9] of the LWR reprocessing costs is \$330/kg which would make the cost of reprocessing mixed oxide thoria as \$412 to \$660/kg if the above ratio is valid. Reference 4 contains a cost estimate for reprocessing U-233-ThO_2 fuel. It is not discussed here since it does not include the Pu component.

Fabrication of recycled U-233 will require remote equipment due to the gamma activity from the U-232 daughters. Reference 1 judges that future fabrication facilities for Pu-UO_2 will also require remote facilities in lieu of the glove box technology now used and that the fabrication costs of mixed oxide and mixed oxide-thoria will be approximately the same. A cost estimate based on segregated fuel recycle is given in Reference 4. Table 9 presents the results of that study. A cost of \$560/kg (1977 dollars) is given for a plant fabricating U-233-ThO_2 fuel rods.

D. Economics

Assuming that the technical problems can be solved, then the fundamental issue relating to acceptance of the denatured fuel cycle by the nuclear power industry is one of economics. The economic issues, however, include not only the actual costs of the denatured fuel cycle, but also any government incentive programs or legislative constraints that affect comparative fuel cycle costs. For acceptance and introduction of the denatured fuel cycle entirely by the private sector where all cost burdens are accepted by the industry, the sole incentive would be a reduction in the fuel cycle costs. At the present time, it is doubtful that the denatured fuel cycle could compete economically with the conventional uranium fuel cycle if the total cost burden were to be borne by industry. The studies, "Assessment of Utilization of Thorium in BWRs," "Assessment of Thorium Fuel Cycles in Pressurized Water Reactors," and "Assessment of the Thorium Fuel Cycle in Power Reactors" (References 3, 1 and 4, respectively) all came to the conclusion there was no economic incentive to adopt the thorium fuel cycle. There is a significant cost penalty if, once adopted, the thorium fuel cycle is not carried out through the life of the reactor.

Table 4 FUEL TYPES ACCOMMODATED BY THE REPROCESSING TECHNIQUES

(Reproduced from Ref. 7)

Process	Fuel Type							Remarks
	U	UO_2	UC	Alloy	Pu	Th	ThO_2	
1. Airox		X						
2. Electrochemical	X				X	X		
3. Halide Volatility	X	X		X	X	X	X	Possibly UC
4. Hydride	X							
5. Ion-Exchange	X	X			X	X	X	Soluble in HNO_3
6. Photochemical	X	X	X	X	X	X	X	
7. Liquid-Liquid	X				X	X		
8. Melt Refining	X							
9. Tin-Nitride	X	X	X	X				
10. Purex	X	X			X			Soluble in HNO_3
12. Salt Transport	X	X	X	X	X	X		
13. Thorex					X	X		Soluble in HNO_3
14. Zincal	X	X						Possibly UC

Table 5 SUMMARY OF RATINGS & PERFORMANCE FACTORS FOR THE 14 PROCESSES
(Reproduced from Ref. 7)

		Process													
Descriptor	Rank	Airox	Electrochemical	Halide Volatility	Hydride	Ion Exchange	Photochemical	Liquid-Liquid	Melt Refining	Tin-Nitride	Purex	Redox	Salt Transport	Thorex	Zincal (Pyrozinc)
1. Technical Complexity	7	8	5	4	3	4	4	7	9	8	3	3	4	3	6
2. Safeguards of Plutonium	10	9	8	5	7	3	3	8	8	8	5	5	5	5	8
3. Magnitude of Waste Problem	8	9	8	4	9	3	4	8	9	9	3	3	6	3	9
4. Sensitivity to Changing Safety Regulations	5	3	7	6	3	4	4	5	5	5	4	4	7	4	5
5. Sensitivity to Change in Fuel Type	5	3	3	8	3	4	10	7	3	7	4	4	8	4	3
6. Maintenance Problems	8	8	4	6	5	5	3	5	5	5	8	8	6	8	5
7. Development Factor	4	4	3	9	3	9	1	3	9	4	10	9	8	10	3
8. Reliability	10	4	7	8	2	8	6	5	7	8	9	9	7	9	6
9. Risk to Population	10	7	8	3	7	4	5	9	9	9	4	4	6	4	9
10. Economic Advantage	5	6	10	8	9	5	9	10	8	10	3	1	9	4	10
11. Decontamination Factor	5	1	2	10	2	3	10	4	1	4	10	10	10	10	2
TOTAL	770	473	483	464	390	366	393	515	536	564	434	420	506	439	506
PERFORMANCE FACTOR		61	63	60	51	48	51	67	70	73	56	55	66	57	66

Table 6 SUMMARY OF COST ESTIMATES (ALL COSTS IN 1975 U.S. $)
(Reproduced from Ref. 7)

Process	Equipment	Total Capital	Operating Cost per annum	Process Cost per kg fuel	Process Cost / Purex Cost
1. Airox	3,354,000	17.590,300	14,190,667	47.30	0.74
2. Electrochemical	3,000,000	12,480,000	4,065,140	13.55	0.21
3. Halide Volatility	4,672,510	20,811,389	8,292,238	27.64	0.43
4. Hydride	4,425,000	16,558,750	5,660,272	18.87	0.29
5. Ion-Exchange	6,830,000	26,318,500	14,558,132	48.53	0.76
6. Photochemical	5,324,000	19,904,300	6,327,688	21.09	0.33
7. Liquid-Liquid	3,400,000	11,460,000	4,145,622	13.82	0.22
8. Melt Refining	13,538,460	39,154,932	9,262,387	30.87	0.48
9. Tin-Nitride	2,850,000	12,382,500	4,641,342	15.47	0.24
10. Purex	6,909,883	32,974,174	19,236,227	64.12	1.00
11. Redox	9,303,366	43,869,227	24,874,654	82.92	1.29
12. Salt Transport	4,280,000	12,438,400	6,348,854	21.16	0.33
13. Thorex	3,341,540	20,898,496	18,145,751	60.49	0.94
14. Zincal (Pyrozinc)	4,625,000	15,648,750	5,045,184	16.82	0.26

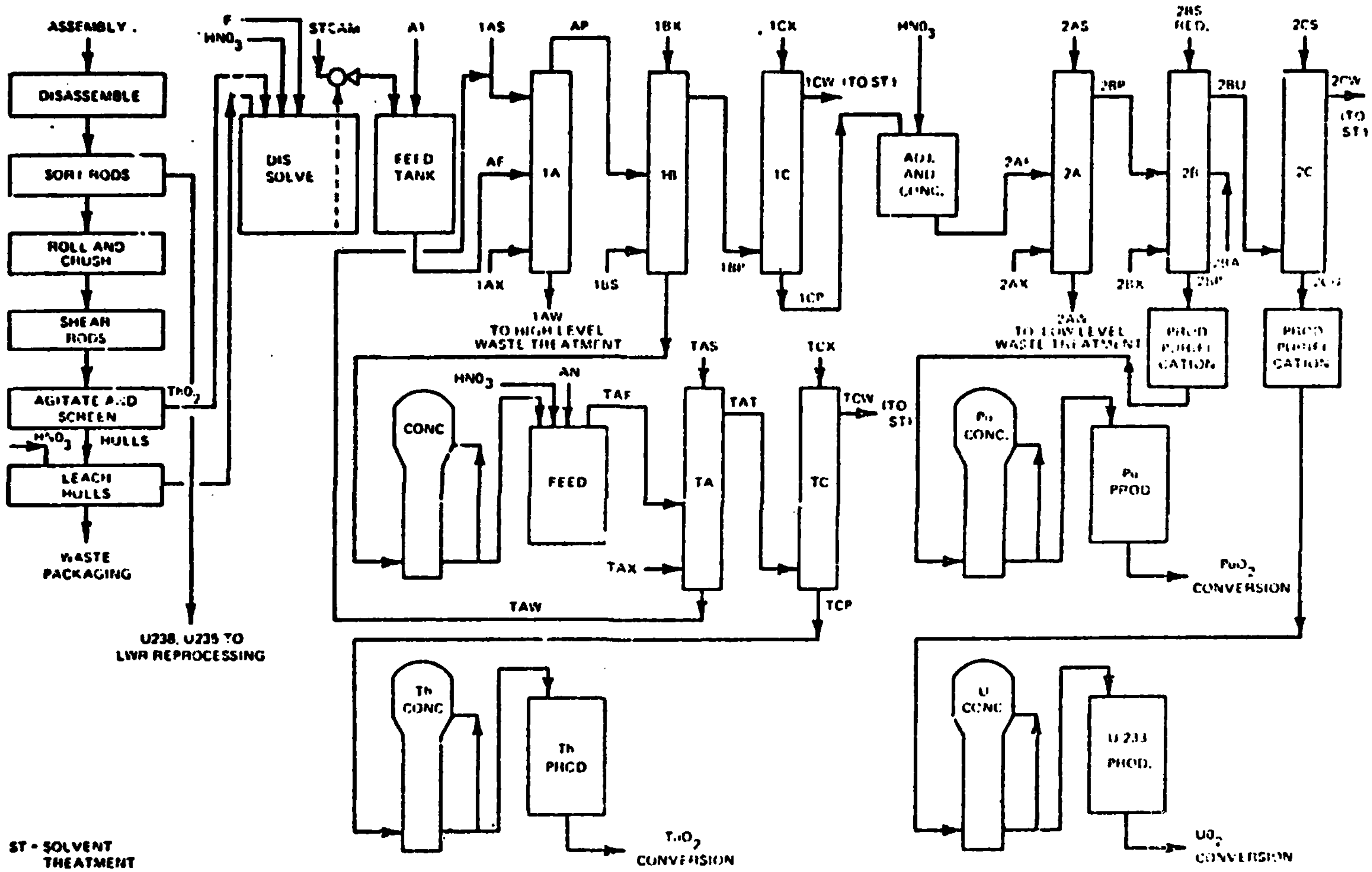


Fig. 1 Proposed pre-breeder fuel reprocessing flowsheet.
(Reproduced from Ref. 8)

Table 7 Th-Pu-U-233 RECOVERY FLOWSHEET
(Reproduced from Ref. 8)

Stream	Relative Flow	Th-232 g/1	Pu g/1	U-233 g/1	AN $\bar{M}$	F^- $\bar{M}$	TBP Vol %	HNO_3 $\bar{M}$	HAN $\bar{M}$
AF	1,000	340	11.1	4.3	0.5	0.6		1	
AS	1,000				0.5			1	
AX	5,000						42.5		
AP	5,000	68	2.22	0.86				0.25	
AW	2,000	<0.3	<0.01	<0.01	0.5	0.3		0.375	
1BS	1,600						42.5		
1BX	2,000							0.5	
1BP	6,600	0.02	1.68	0.65				0.05	
1BT	2,600	131	<0.01	<0.01				0.74	
1CX	13,000							0.1	
1CP	13,000	0.01	0.854	0.325				0.13	
1CW	6,600							0.01	
TAF	1,000	340			0.5			-0.2	
TAS	1,000				0.5			-0.2	
TAX	5,000						42.5		
TAT	5,000	68					42.5		
TAW	2,000	<0.1%			0.5			-0.2	
TCX	3,700							0.01	
TCP	3,700	92						0.01	
TCW	5,000						42.5	4×10^{-4}	
2AF	325		33.6	13				5.2	
2AS	325							0.5	
2AX	680						12		
2AP	880		12	4.6				0.0286	
2AW	650		0.006	1×10^{-6}				2.89	
2BS	180							1	0.2
2BX	180							15	
2BP	180		60					1.99	
2BU	1,050		$<4 \times 10^{-6}$	3.8				0.105	
2BA	23							13	
2CX	530							0.01	
2CW	1,060			$<1 \times 10^{-11}$			15	4×10^{-4}	
2CU	530							0.215	
U Prod.				470				13.3	
Th Prod.		700						0.08	
Pu Prod.			350					11.6	

Table 8 ADDITIONAL THORIA PROCESS REQUIREMENTS BEYOND THOSE FOR THE LWR PUREX PROCESS

(Reproduced from Ref. 8)

Item	Function and Requirements
Fuel storage	Additional storage required to store 300 days rather than 170 days for LWR.
Bundle disassembly	Permits segregation of U from Th rods. LWR uses full bundle shear.
Tube sorting	Separates U tubes from Th tubes. Mechanical sorting used.
Tube rolling fuel chrushing	Expands tube and crushes fuel in tube.
Fuel cladding separator	Mechanical screen device separates fuel from cladding pieces. Assumes tube shear and whole bundle shear are comparable in cost.
Special dissolvers	Constructed of material to contain low concentration of fluoride ion in nitric acid.
Solvent extraction	Additional cycles required for U-233 and Th purification. Two solvent concentration and two solvent treatment systems.
Aluminum nitrate (AN) makeup tanks	AN not used in LWR. Requires added instrumentation.
Recycle concentrator	Concentrates AN solution from thorium cycle for reuse in first cycle solvent extraction. Includes additional instrumentation.
High level wastes	Increase in volume over LWR wastes of about 0.8 ft^3/Mt due to AN in waste.
U-233 conversion and load-out	Convert U nitrate to oxide.
Added safeguards costs	Provide safeguard surveillance for additional fissile component.
Personnel	Assumes nine more operators for three-shift coverage due to additional equipment plus one more instrument technician.

It was assumed that the costs for thorium conversion and load-out would approximately balance the U to UF_6 conversion costs of the LWR plant.

Table 9 ESTIMATED FABRICATION COST COMPARISON[a]
(Reproduced from Ref. 4)

Reactor Type	Fuel Material	Relative Cost Factors				Estimated Costs ($/kg)[b]
		Capital	Hardware	Operating	Total	
PART A						
LWR (PWR)	$(^{235}U\text{-}U)O_2$	0.33	0.38	0.29	1.00	150[c]
	$(Pu\text{-}U)O_2$	1.49	0.38	1.45	3.32	500
	$(^{235}U\text{-}Th)O_2$	0.50	0.42	0.44	1.36	200
	$(^{233}U\text{-}Th)O_2$	1.98	0.38	1.45	3.81	570
	$(Pu\text{-}Th)O_2$	1.49	0.38	1.53	3.40	510
CANDU	Normal UO_2	0.33	0.09	0.11	0.53	80
	$(Pu\text{-}U)O_2$	1.49	0.09	0.50	2.08	310
	$(^{233}U\text{-}Th)O_2$	1.98	0.09	0.50	2.57	390
	$(Pu\text{-}Th)O_2$	1.49	0.09	0.53	2.11	320
FBR (L.M.)	$(Pu\text{-}U)O_2$	3.19	0.58	2.10	5.87	880
	$(Pu\text{-}U)C$	2.68	0.37	1.66	4.71	710
	$^{233}U\text{-}Th$	2.73	0.35	1.60	4.68	700
FBR (Gas)	$(Pu\text{-}U)O_2$	3.19	0.90	2.29	6.38	960
	$(^{233}U\text{-}Th)O_2$	4.55	0.90	2.40	7.85	1,180
	$(Pu\text{-}Th)O_2$	3.64	0.90	2.40	6.94	1,040
PART B						
HTGR	$^{235}UO_2\text{-}ThO_2$	0.26	0.42	0.32	1.00	400[d]
	$^{233}UCO\text{-}ThO_2$	1.21	0.42	0.95	2.58	1,030
	$^{235}UO_2\text{-}UO_2$	0.26	0.32	0.32	0.90	360
	$PuO_2\text{-}ThO_2$	1.21	0.42	0.94	2.57	1,030

[a]All cost comparisons are relative to the given base case factors.

[b]1977 dollars assumed for total kilograms of heavy metal product with a plant output of 2 metric tonnes per day and 260 full operating days per year (520 MT/year).

[c]Base case for metal clad fuel rods based on FABCOST 9 estimates (A. L. Lotts et al., A/CONF, 49/P/062, 1972) escalated to 1977 with additions for current scrap and waste treatment requirements.

[d]Base case for all HTGR (Prismatic Fuel Element) cases based on data in "Summary Program Plan, Alternate Program for HTGR Fuel Recycle," April 11, 1975, Draft.

The principal factors that result in a nominally-higher cost for the denatured fuel cycle include the following:

— thorium ore mining and procurement;

— additional cost of blending operations;

— higher enrichment and SWU requirements for the initial core loading;

— greater difficulty of reprocessing fuel containing thoria; and

— remote recycle fuel fabrication and additional shipping costs resulting from the inherent U-232 contamination and its associated gamma radioactivity.

Offsetting these factors are the better neutronic properties of U-233 (conversion ratio and reactivity), the reduced power peaking problems of recycled fuel, the smaller radiological hazard of U-233 compared to plutonium, improved uranium resource utilization, and the reduced risk of weapons proliferation.

Even in the future, assuming chemical reprocessing is permitted, it is unlikely that the denatured fuel cycle can compete successfully, at least until uranium ore costs have risen quite substantially above present levels. Government funding will likely be necessary to support the requisite research and development program for the denatured fuel cycle. In addition, government incentive programs may be required to induce acceptance of the denatured fuel cycle by industry. These may be direct subsidies, indirect subsidies in the form of cost guarantees of buy-back policies, and/or legislative restrictions—for example, prohibiting recycle of plutonium while permitting recycle of the denatured fuel (uranium with U-233 included).

The subjective issues affecting the utilization of a denatured U-Th fuel cycle necessitates assessment of the incentives. If the alternate cycle were sufficiently attractive, economically and technically, its inherent merits would cause it to be accepted by the industry. However, the principal attractive feature of the denatured cycle—nonproliferation—does not naturally fit into the commercial arena, especially in the case of reactors-for-export, where the higher cost expected for the denatured fuel cycle (in the absence of government subsidies) could be a major competitive disadvantage.

E. Subjective Issues

The long term implications of alternative fuel cycles has been addressed in two ANL reports.[10,11] Very briefly, these reports conclude that there is limited period of time, perhaps 20-40 years, when thorium fueled converters could be used before they began to exhaust the fissile inventory and foreclose the breeder option. In their opinion, the best non-proliferation alternative would be Pu fueled breeders in secure nuclear energy centers producing U-233 in thorium blankets. The denatured U-233 could then be used to fuel off-site converters.

Appendix J of Reference 4 addresses the "institutional considerations" of the thorium fuel cycle. The authors consider the use of converters operating on the thorium fuel cycle as a contingency to the breeder development scenario. The text of Appendix J is quoted below:

> "This study has shown that adoption of thorium cycles in thermal reactors results in better ore utilization than does use of the uranium cycle. At the same time, if Fast Breeder Reactors (FBRs) are commercialized on planned schedules, their use with the uranium cycle gives substantially better ore utilization in a growing nuclear economy. Thus, development of thorium fuel cycles corresponds to developing a contingency position for the case of a delay in FBR introduction. Further, thorium fuel cycles provide flexibility in the future if FBRs are introduced on schedule. If anticipated trends for relatively low nuclear electricity growth hold, and the breeder can be commercialized on the present ERDA schedule, the contingency position is not necessary. However, if nuclear electricity demand accelerates and/or the breeder is delayed significantly, then a contingency position is prudent. Advocates of the LWR-LMFBR scenario might argue that any money spent on contingency fuel cycles could be better utilized on the FBR program to increase the probability of meeting the present schedule. Those who advocate development of a contingency position think it unwise to risk everything on one system which may not be delivered on time.

Both arguments have merit; so deciding between them requires a realistic assessment of the costs, risks, and benefits.

"There is a school of thought which believes high gain converter reactors can replace FBRs in the nuclear picture, and provide the means to generate electricity until more advanced systems (fusion, solar) are commercially available on a large scale. Whether this is practical depends very much upon the nuclear power growth, the amount of natural U_3O_8 available at reasonable costs, and the introduction schedule of the advanced systems. Based on present estimates, FBRs are needed to maintain anticipated nuclear power growth. However, introduction of high gain converters (with conversion ratios approaching unity) does permit a substantial increase (relative to LWR use alone) in the nuclear power level which would be practical for the case of a substantial delay in the commercial use of FBRs. The results obtained here indicate that high priority should be given to the FBR, but that a contingency position can and should be developed which requires development and application of the thorium fuel cycle.

"Use of thorium fuel cycles in thermal reactors will require the development of economic fuel recycle technology. Utilities will be reluctant to invest in the higher fuel inventory of thorium cycles unless there is a demonstrated, economic fuel recycle technology available to them. The above is particularly true of thorium-cycle LWRs and HWRs (HTGRs can store fuel for a number of years more economically than can the other concepts, but would require fuel recycle about 10 years after introduction). Further, early introduction of the thorium fuel cycle would require use of present reactor designs. Thorium fuel cycle development would be expedited by close collaboration with reactor vendors as well as with utilities.

"The reference nuclear development scenario for the U.S. calls for Light Water Reactors (LWRs)

> to provide power and produce plutonium to be used in LMFBRs. According to the simple model presented in Appendix P, about 60% of the plutonium produced in LWRs over the next 30 years must be stockpiled for LMFBR inventories. If thorium fuel cycles were introduced in LWRs, the extent of introduction would be constrained by the requirement to stockpile plutonium. The investment in R&D needed to commercialize thorium cycles in LWRs may not be justified in view of the modest improvements over the uranium cycle with uranium and plutonium recycle and the constraints imposed by the need for plutonium for use in Fast Breeder Reactors."

It is clear that convincing the nuclear industry that the denatured fuel cycle could have a positive effect on the international proliferation issue, and that the benefits are worth the additional expense and inconvenience, will be a major task.

III. DENATURED FUEL CYCLE PRELIMINARY DEMONSTRATION PROGRAM

Essentially, the thorium utilization program has been started, in that the studies and conceptual fuel management studies conducted over the past few years form the basis from which to prepare a more detailed program plan. The Program is structured around five major objectives:

- Demonstration Program Planning
- Proof-of-Principle R&D
- Reprocessing/Remote Fabrication Facility
- Ore Mining and Processing
- Utility Involvement

The program objectives are discussed in more detail below:

A. Demonstration Program Planning

It will be necessary to develop a detailed implementing schedule for the thorium utilization program. Part of the overall program direction will require obtaining public and utility input to the program. Further studies will be necessary to support the program planning. These studies will include updates on nonproliferation advantages, resource utilization, fuel cycle economics, safety issues, and environmental impact assessments.

B. Proof-of-Principle R&D

Once the overall R&D effort has been defined in detail, programs on critical path items should be initiated immediately. These programs will include basic physical measurements of the fuel mixture at all temperatures of interest, including high temperatures for input to safety analyses. An irradiation program will have to be instituted to demonstrate the fuel performance of both the startup fuel and the equilibrium recycle fuel. Pilot scale reprocessing and remote fuel fabrication facilities will need to be built or remodeled from existing facilities.

It seems likely that at least two proof-test irradiations will be necessary for both initial and recycle fuel: a demonstration irradiation of three of four fuel assemblies, followed by prototype irradiation of a full core loading of U-Th oxide fuel. Preceding, and concurrent with, these proof-test irradiations, a program for direct measurement of some important design parameters (e.g., thermal conductivity, melting points, eutectic formation, material segregation, fission gas release, etc.) will likely be necessary. These irradiation tests will not only provide a base of experimental data, but, of almost equal importance, will allow some experience to be gained in the licensing process.

C. Reprocessing/Remote Fabrication Facility

Concurrently, other R&D projects will be required to establish costs associated with ore availability, fuel fabrication, reprocessing, and recycling. These data will serve as a base for defining the denatured fuel cycle costs and for identifying any government incentive programs necessary to encourage industry acceptance.

Eventually, construction of a pilot Reprocessing/Remote Fabrication Facility will be necessary. Conceptual design and site selection should begin early. Preliminary design and detailed cost estimates should follow the conceptual design. The construction should start in time to meet the schedule requirements of the Proof-of-Principle phase.

D. Ore Mining and Processing

A detailed assessment of both international and domestic thorium reserves should be performed. Techniques for ore recovery and the environmental considerations and cost should be made. Impact of worldwide demand for thorium should be assessed (see Reference 12 for a discussion of the current availability).

E. Utility Involvement

As soon as possible, utility involvement in the program should be developed. This could follow the structure of the current

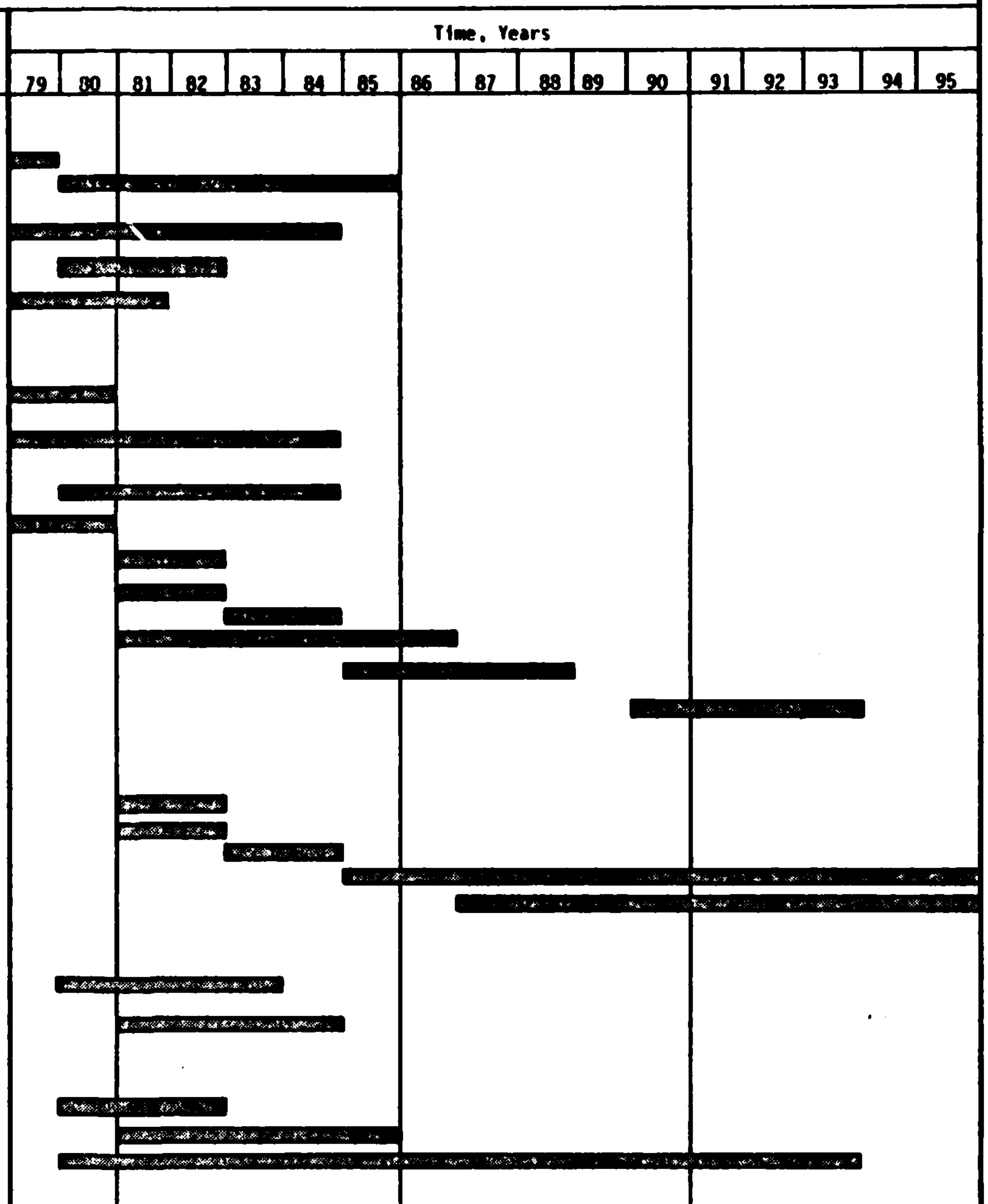
LWR High Burnup Program. Any power plant modifications required to handle recycle thorium fuel should be identified early. Surveys of industry attitudes, and information exchange meetings, are among the possibilities that could lead to industry participation and support. Resolution of the subjective or political issues can be quite difficult, particularly if it is realized that the industry is inclined to translate all other considerations into one of economics. Convincing the nuclear industry that the denatured fuel cycle could have a positive effect on the international proliferation issue, and that the benefits are worth the additional expense and inconvenience, will be a major task.

F. Preliminary Program Schedule

A preliminary schedule of the Thorium Utilization Program has been developed, and is presented in Table 10. Revisions will be made as the subtasks within each program objective are developed in detail.

Table 10 PRELIMINARY DEMONSTRATION PROGRAM PLAN

PROGRAM TASK



DEMONSTRATION PROGRAM PLANNING

- Establish detailed program schedule through year 2000
- Obtain utility and public input to program
- Fund more accurate studies on non-proliferation, economics, resource utilization, nuclear electric growth scenarios, reactor performance, thorium fuel performance
- Prepare environmental impact statement for thorium fuel cycle
- Determine extent of government support and nature of incentives required to implement thorium fuel cycle

PROOF-OF-PRINCIPLE R&D

- Select contractor to furnish technical direction to R&D
- Measure physical, chemical, and nuclear properties of denatured thorium fuel over all operating conditions including postulated accident conditions
- Modify fuel performance and safety analysis codes to accept denatured fuel input
- Design startup fuel pins
- Fabricate first group of PWR and BWR test pins for demonstration irradiation
- Design recycle fuel pins
- Fabricate first group of PWR and BWR test pins of recycle fuel
- Build pilot scale reprocessing facility
- Fabricate demonstration cores of prototype fuel for both PWR and BWR
- Reprocess initial cores and fabricate demonstration recycle cores

REPROCESSING/REMOTE FABRICATION FACILITY

- Perform conceptual design
- Select potential sites
- Perform preliminary design and obtain detailed costs
- Start licensing of facility
- Start construction

ORE MINING AND REPROCESSING

- Perform thorough study of potential resources and mining industry growth scenarios.
- Identify any reprocessing R&D required.

UTILITY INVOLVEMENT

- Fund power plant modification study
- Fund licensing requirements study
- Arrange utility participation in irradiation R&D

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